# On the Impossibility to Measure the Total Neutron- and Proton Induced Nonmesonic Decays for $^3_\Lambda$H

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## Abstract

Based on realistic calculations for the nonmesonic decay rate of $^3_\Lambda$H we demonstrate, that in principle it is not possible to measure the total n- and p- induced decay rates and as a consequence $\Gamma_n/\Gamma_p$ for that lightest hypernucleus. For the nonmesonic decay process the calculations are performed with modern YN forces based on various meson exchanges and taking the final state interaction among the three nucleons fully into account. Our findings have consequences also for the interpretation of experimental $\Gamma_n/\Gamma_p$ ratios for heavier hypernuclei where severe discrepancies exist to theoretical $\Gamma_n/\Gamma_p$ ratios.

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# I. INTRODUCTION

There is a longstanding discrepancy between the theoretical ratio of the total neutron induced nonmesonic decay rate $\Gamma_n$ to $\Gamma_p$, the total decay rate for the proton-induced nonmesonic decay rate of various hypernuclei to experimental data [1]. The experimental values are typically around 1 except for the very light hypernucleus $^4_\Lambda$He [7,8], while theoretical evaluations lead to 0.05 - 0.2. The experimental value for $\Gamma_n$ is estimated either from neutron measurements and/or deduced from the measured values of the total nonmesonic decay rate $\Gamma_{nm}$ and of $\Gamma_p$ as

$$\Gamma_n \equiv \Gamma_{nm} - \Gamma_p \tag{1}$$

Apparently this relation can not be strictly true due to interferences. The quantity $\Gamma_p$ is determined experimentally from measuring single proton spectra and assuming that those protons are generated by the p-induced decay. Again this can not be strictly true since the n-induced decay leaves behind spectator proton(s) and final state interactions can carry momentum from neutrons to protons. We shall shed light in this article on those critical issues. On the theoretical side one faces the nuclear many body problem. Rigorous solutions based on realistic modern baryon-baryon forces are not in sight. Therefore shell model pictures supplemented by Jastrow type two-body correlations are typically being used and final state interactions are established by optical potentials. It appears difficult to estimate quantitatively the uncertainty of the theoretical predictions. In such a situation a view on very light systems is of increasing interest. In the 3-baryon system bound and scattering states can be rigorously gained based on modern realistic baryon-baryon forces [2]. Therefore uncertainties about the quality of the hypernucleus wavefunction and final state interactions are absent. In the four-body system first rigorous solutions for bound states ($^4_\Lambda$H and $^4_\Lambda$He) already appeared [3]. The mesonic and nonmesonic decays of $^3_\Lambda$H have been calculated [2,4] but there are only few data to compare with. Some mesonic decay rates for $^3_\Lambda$H for which data are available agree rather well with that theory. Though there are state of the art

calculations no data are available for the very small nonmesonic decay rates of $^3_\Lambda$H. We would like to use in this article that theoretical insight to throw light on the questionable issues mentioned above. In [2] we found that the nonmesonic decays of $^3_\Lambda$Hleading to a final deuteron and a neutron are suppressed by about a factor 10 with respect to the full breakup processes. Therefore we shall neglect those two-body fragmentation decay channels of $^3_\Lambda$Hin the following - except for pointing out that there a separation of n- and p- induced decays is clearly impossible. This is already evident from the fact that $\Gamma_n^{n+d} + \Gamma_p^{n+d} = 0.39 \times 10^7 \text{s}^{-1}$, whereas the total n+d decay rate $\Gamma^{n+d} = 0.66 \times 10^7 \text{s}^{-1}$. Clearly there is a strong interference between the n- and p-induced decays.

The exclusive differential n+n+p decay rate has the form [2]

$$
d\Gamma^{n+n+p} = \frac{1}{2} \sum_{m,m_1,m_2,m_3} |\langle \Psi^{(-)}_{\vec{p}\vec{q}m_1m_2m_3} | \hat{O} | \Psi_{^3_\Lambda H,m} \rangle|^2 2\pi d\hat{k}_1 d\hat{k}_2 dE_1
$$
$$
\times \frac{M_N^2 k_1^2 k_2^2}{|k_1(2k_2 + \vec{k}_1 \cdot \hat{k}_2)|} \tag{2}
$$

Here $\hat{k}_1$ and $\hat{k}_2$ denote the directions of two detected nucleons (see [2] for further information). We have shown in [2] that there are regions in phase-space which are populated by n- and p- induced decays and therefore an experimental separation for those contributions is impossible. But there are also regions in phase-space which are rather cleanly populated by either n- or p- induced processes, but not both. Therefore one has to be satisfied with certain fractions of $\Gamma_n$ and $\Gamma_p$, defined by integrations over certain subregions of the total phase-space. In this manner one can measure n- and p- induced process separately. The fact that certain parts of the phase-space are populated by both processes coherently makes it obvious that by no means one will be able to access experimentally $\Gamma_n$ and $\Gamma_p$ separately. Nevertheless we would like to demonstrate this explicitly in the approach to $\Gamma_p$ which is being used for heavier hypernuclei [1]. There one investigates the semiexclusive decay process in which only one proton is detected. Therefore we shall study in this article the single differential decay rate $d\Gamma/dE_p$ and in addition also $d\Gamma/dE_n$ and investigate whether they can be separated into n- and p- induced contributions and whether certain energy ranges are dominated by one or the other process.

Our results are based on rigorous solutions of the Faddeev equations for $^3_\Lambda$Hand the 3N final scattering states. We use the YN Nijmegen potential [5] which includes $\Lambda$-$\Sigma$ conversion. It turned out that this potential produces the experimental $^3_\Lambda$Hbinding energy without further adjustment [6]. For the NN forces we used the Nijmegen' 93 potential [9]. We expect no dependence on the choice among the most modern NN potentials. For the hypertriton this has been verified. The importance of the final state interaction is demonstrated by also presenting results where the 3N scattering state in the nuclear matrixelement occurring in Eq. (2) is replaced by 3N plane wave states. This extreme approximation will, like in [2], be denoted by symmetrized plane wave impulse approximation (PWIAS), whereas the calculation with final state interaction will be called "FULL". In Fig. 1 we show $d\Gamma/dE_n$, $d\Gamma_n/dE_n$ and $d\Gamma_p/dE_n$ in PWIAS. The quantity $d\Gamma \: / \: dE_n$ has two peaks, one at very low neutron energies and one close to the maximal possible neutron energy. The peak at the higher energy is fed by the n- and p- induced processes as is obvious from the corresponding peaks in $d\Gamma_n/dE_n$ and $d\Gamma_p/dE_n$. Clearly in both processes a high energetic neutron is produced. Surprisingly for us $d\Gamma_n/dE_n + d\Gamma_p/dE_n$ sum up to $d\Gamma/dE_n$ with an error smaller than 5 %. The interference terms are therefore numerically very small. For very small neutron energies $d\Gamma_n/dE_n$ dies out, since the n- induced process creates mostly high energetic neutrons. The p- induced process, however, $d\Gamma_p/dE_n$, exhibits a strong peak at very low neutron energies, which is caused by the (spectator) momentum distribution of the neutron in $^3_\Lambda$H. Clearly a measurement of the decay rate $d\Gamma/dE_n$ as a function of the neutron energy will not allow to separate the n- and p- induced processes - except at very low neutron energies, where the energy distribution of the neutrons, however, is not determined by the $\Lambda$-decay process. That picture does not change qualitatively if one turns on the final state interaction as can be seen in Fig 2. Quantitatively, however, the rates are quite different. We can see a reduction factor of about 2 and the neglection of FSI would be disastrous in a quantitative analysis of data. Now the sum $d\Gamma_n/dE_n + d\Gamma_p/dE_n$ equals $d\Gamma/dE_n$ only within about 12 %.

The situation for a separation of n- and p- induced processes appears somewhat more

favourable if one regards the single particle decay rates as a function of the proton energy. Our results are shown in Fig. 3 for PWIAS and Fig. 4 for the "FULL" calculation. For large proton energies nearly all protons result from the p- induced process : $d\Gamma/dE_p \approx d\Gamma_p/ dE_p$ in case of PWIAS. The quantity $d\Gamma_n/dE_p$ can not produce high energetic protons except due to FSI and this is indeed visible by comparing Figs. 3 and 4. $d\Gamma_n/dE_p$ exhibits, however, the very low energetic proton peak from the spectator proton in $^3_\Lambda$H. Also note again the reduction factor of about 2 caused by FSI.

Let us now quantify the question, whether integrated proton distributions can provide a good estimate for $\Gamma_p$. Clearly the very low energetic peak should be excluded and one has to start integrating $d\Gamma/dE_p$ from the highest possible proton energy $E_p^{max}$, downwards. Thus we compare the integrals

$$\Gamma(E_p) \equiv \int_{E_p}^{E_p^{max}} dE_p' \frac{d\Gamma}{dE_p'} \tag{3}$$

$$\Gamma_p(E_p) \equiv \int_{E_p}^{E_p^{max}} dE_p' \frac{d\Gamma_p}{dE_p'} \tag{4}$$

and

$$\Gamma_n(E_p) \equiv \int_{E_p}^{E_p^{max}} dE_p' \frac{d\Gamma_n}{dE_p'} \tag{5}$$

as functions of $E_p$. The results are displayed in Figs. 5 and 6 for PWIAS and FULL. We see that in the case of PWIAS down to about $E_p \approx 50$MeV the two curves $\Gamma(E_p)$ and $\Gamma_p(E_p)$ are close to each other within less than 5% and only then start to deviate strongly. While $\Gamma_p(E_p)$ flattens out and approaches $\Gamma_p = \Gamma(E_p = 0)$, $\Gamma(E_p)$ receives contributions from the n-induced process. The situation is not so favourable, however, for the case FULL. Around $E_p$=60 MeV the relative deviation $|\Gamma_p(E_p) - \Gamma(E_p)|/\Gamma_p(E_p)$ is about 10 % and increase to about 20 % around $E_p$=15MeV. Below that the deviation increases up to 30 %. Note also the relative factor of about 2 between PWIAS and FULL. We have to conclude that an estimate for $\Gamma_p$ from $d\Gamma/dE_p$ is only possible within an error of about 30 %. If one is satisfied with a fraction of $\Gamma_p$ the error can be reduced to about 10 %.

A well defined manner to receive information on the p- and n-induced decays separately is to use the differential decay rate of Eq.(2) as described in [2]. There are certain regions in phase space which are populated only by the p- induced decay and others which are populated only by the n-induced decay. In this manner one does not get the total $\Gamma_p$ or $\Gamma_n$, but at least well defined fractions thereof.

Now we would like to address the question, whether $\Gamma_n$ can be found via Eq. (1) in case of $^3_\Lambda$H. This is a pure theoretical issue since, as we just demonstrated, $\Gamma_p$ can not be measured for $^3_\Lambda$H. Surprisingly enough Eq. (1) is valid. As seen from Table V in [2] we have

$$\Gamma_n^{FULL} = 0.17 \times 10^8, \Gamma_p^{FULL} = 0.39 \times 10^8, \Gamma_n^{FULL} + \Gamma_p^{FULL} = 0.56 \times 10^8 \qquad (6)$$

That sum has to be compared with $\Gamma^{FULL} = 0.57 \times 10^8$, which treats the full process correctly as a coherent sum of the n- and p-induced decays. These numerical results validate Eq.(1) in the case of $^3_\Lambda$H.

Finally we note that our theoretical result for the ratio of the total n- and p-induced decay rates in case of $^3_\Lambda$His $\Gamma_n/\Gamma_p = 0.44$.

Since $\Gamma_p$ in the case of $^3_\Lambda$Hcan not be measured, it appears advisable to concentrate directly on $d\Gamma/dE_p$ and $d\Gamma/dE_n$ and compare those distributions to theory. This is an alternative to the above mentioned exclusive processes. While measurements of the nonmesonic decay of $^3_\Lambda$Happear to be far away, data for the four-body hypernuclei already exist [7,8] and theoretical predictions can be expected to come up in the near future. This will then allow interesting tests of the nonmesonic decay matrixelements, which will be based on realistic four-body wavefunctions and various meson-exchange operators [2,10], which drive the nonmesonic decay process.

**ACKNOWLEDGMENTS**

calculations have been performed on the CRAY T90 of the John von Neumann Institute for Computing, Jülich, Germany.

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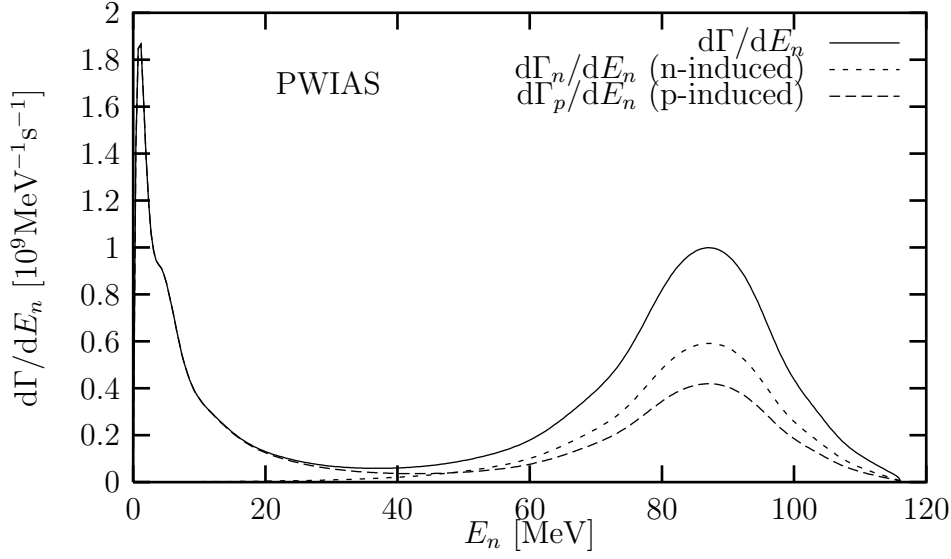[10] A. Parreńo, A. Ramos, C. Bennhold, Phys. Rev. **C 56**, 339 (1997).

FIG. 1.    The single neutron decay rates $d\Gamma/dE_n$, $d\Gamma_n/dE_n$ and $d\Gamma_p/dE_n$ in PWIAS as a function of the neutron energy $E_n$. A separation in n- and p-induced processes is not possible. The peak at very low $E_n$'s shows directly the momentum distribution of the neutron in ${}^3_\Lambda$H.
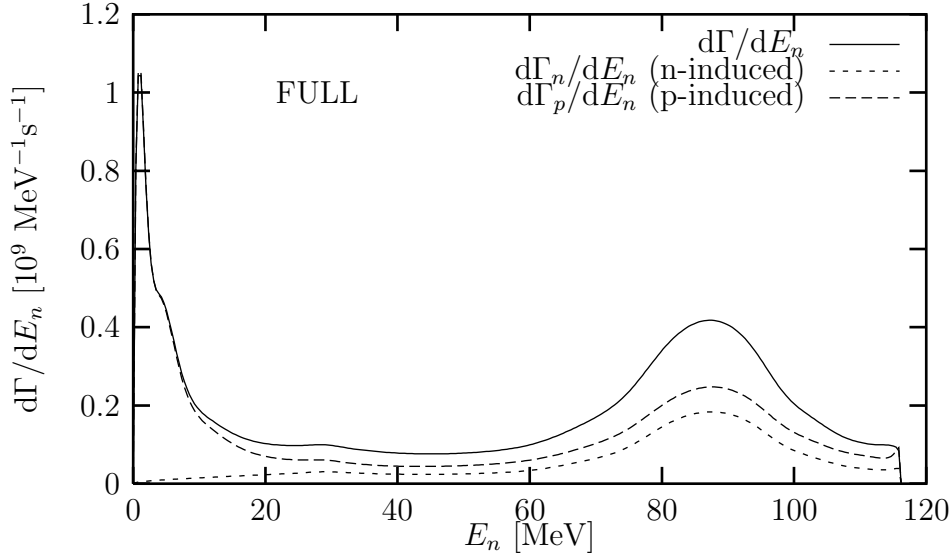


FIG. 2.    The same as in Fig. 1 for the FULL calculation. The peak at very low $E_n$'s is now also influenced by final state interactions.
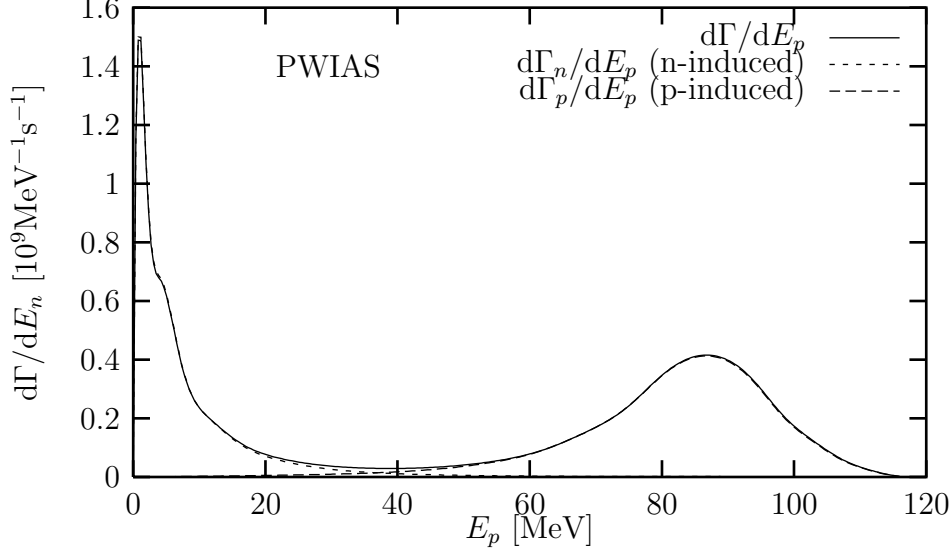
FIG. 3. The single proton decay rates $d\Gamma/dE_p$, $d\Gamma_n/dE_p$ and $d\Gamma_p/dE_p$ in PWIAS as a function of the proton energy $E_p$. Now a separation in n- and p-induced processes would be possible for $E_p$ larger than about 50 MeV. The peak at very low $E_p$'s shows directly the momentum distribution of the proton in $^3_\Lambda$H.
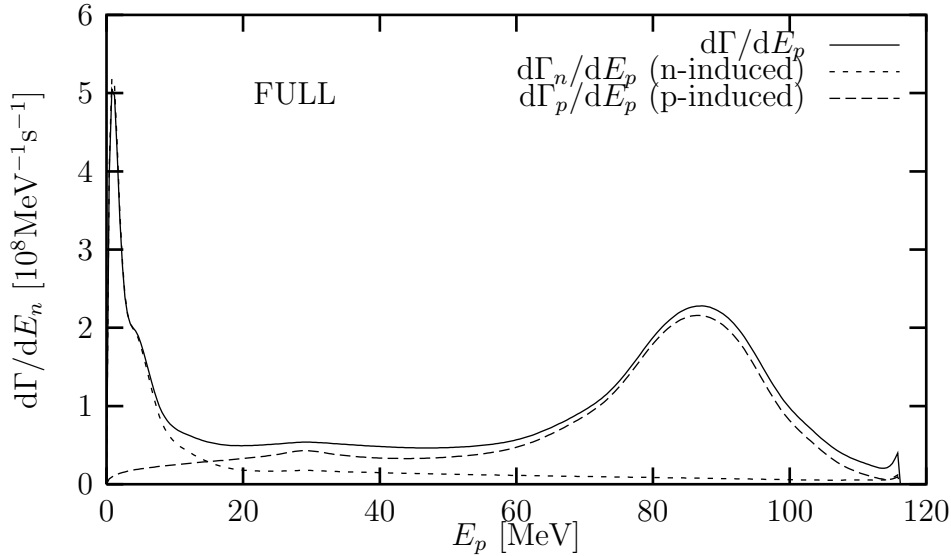


FIG. 4. The same as in Fig. 3 for the FULL calculation. The final state interaction causes now small contributions of high energetic protons resulting from the n-induced decay. Also the peak at very low $E_p$'s is now influenced by final state interactions.
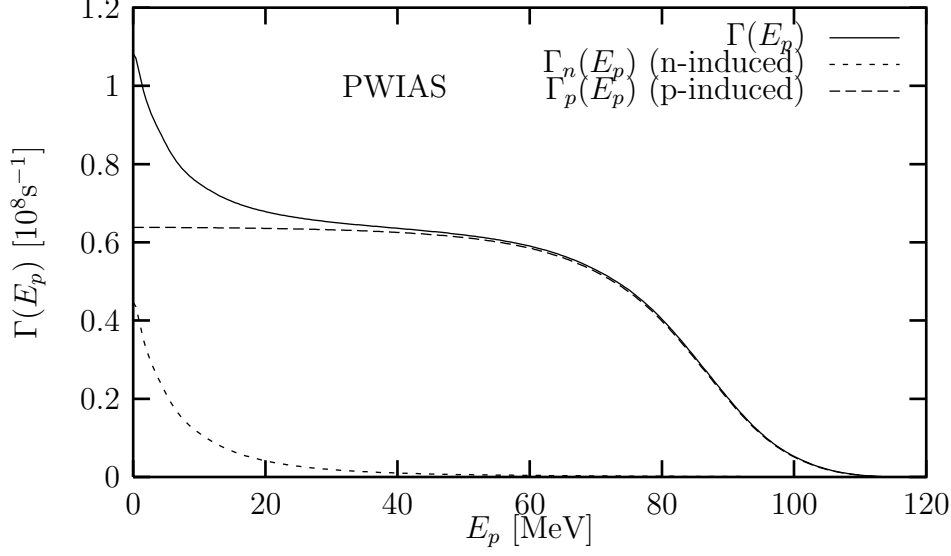
FIG. 5.    The integrated single proton decay rates according to Eqs.(3)-(5) for PWIAS. For $E_p \geq 50$MeV $\Gamma_p(E_p) \approx \Gamma(E_p)$.
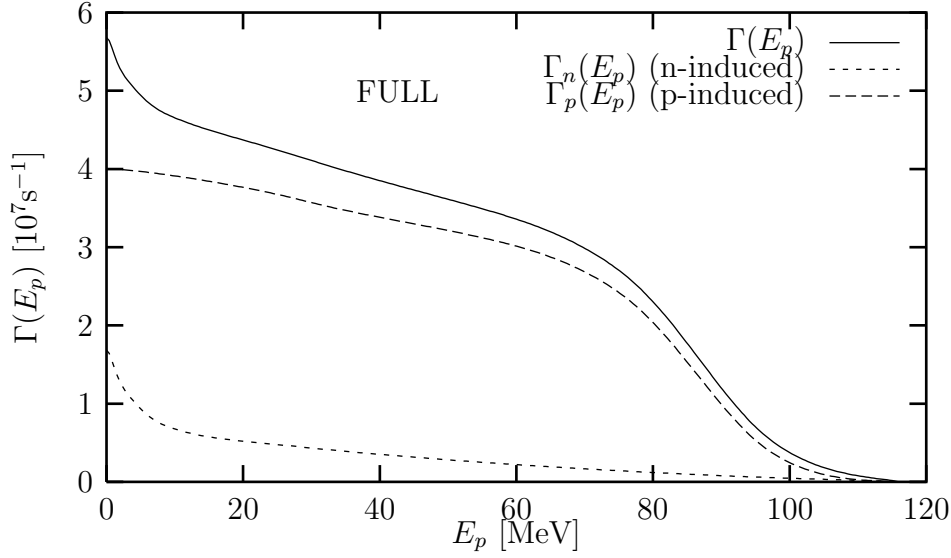


FIG. 6.    The same as in Fig. 5 for FULL. Now the influence of the n-induced decay does not allow to estimate $\Gamma_p(E_p)$ by $\Gamma(E_p)$.